Int. Conf. on Computational Methods for Coupled Problems in Science and Engineering
COUPLED PROBLEMS 2009
B. Schrefler , E. Oñate and M. Papadrakakis (Eds)

HYDRAULIC RESPONSE TO A SHAFT EXCAVATION IN CALLOVO-OXFORDIAN CLAY

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Key words: Coupled analysis, argillaceous rocks, hydro-mechanical excavation boundary condition, permeability increase related to damage.

Summary. This document presents a coupled hydro-mechanical (HM) numerical analysis, using Code_Bright, simulating the excavation of the main access shaft to the underground laboratory of Bure (France) in Callovo-Oxfordian Clay. The work consists in the description of the HM formulation using a specially developed constitutive law and in the discussion of the simulation results. The mechanisms at the origin of the water pressure response are analysed with special emphasis on the influence of the mechanical and hydraulic boundary conditions used for the shaft excavation. Shaft convergence and permeability evolution measured by ANDRA (Modex-REP mine-by-test, [1,2]) during the shaft excavation are compared with the modelling results to illustrate the model capability to reproduce excavation induced damage and to relate it to permeability increase.

1 HM FORMULATION AND CONSTITUTIVE MECHANICAL LAW

The formulation used in the Finite Element code Code_Bright is based on a multi-phase/multi-species approach [3]. In this work, two phases are considered, solid (s) and liquid (l) corresponding to the two species: mineral and water (w). The solution of the coupled HM problem requires the simultaneous solution of the mass balance of solid, the mass balance of water in saturated conditions and the balance of momentum (equation (1), (2) and (3), respectively).

$$\frac{\partial(\rho_s(1-n))}{\partial t}+div(\mathrm{j}_s)=0 \tag{1}$$

$$\frac{\partial(\rho^w n)}{\partial t} + div(\mathbf{j}^w) = f^w \tag{2}$$

$$div(\sigma) + \rho g = 0 \tag{3}$$

The notation used is as follows: n is the porosity, ρ_s is the density of the solid, $\mathbf{j_s}$ is the mass flux of solid, ρ^w is the density of water, $\mathbf{j^w}$ is the vector of mass flux of water, f^w is the source/sink term of water, $\boldsymbol{\sigma}$ is the stress tensor, ρ is the density of the rock and $\mathbf{g}$ the gravity acceleration.

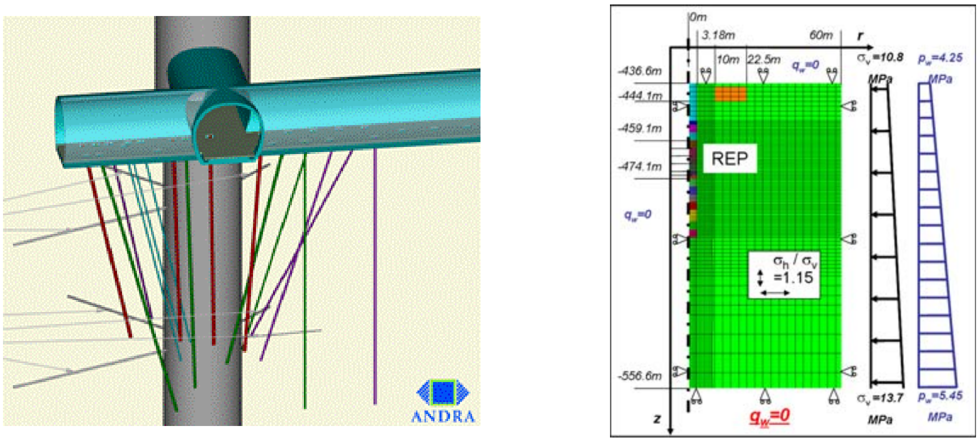
The formulation must be completed with a number of constitutive laws that describe the various phenomena under consideration. The density of the solid and the density of the water are dependent on the total mean pressure and the water pressure, respectively. The advective water flux is described by Darcy's law. Those laws are described elsewhere [3]. Finally, a mechanical constitutive law especially designed for argillaceous rocks is used to relate the effective stress ($\sigma' = \sigma - b.p_w$, where b is Biot's coefficient and p_w the water pressure) and skeleton deformation. This law was described in detail in [4]. Argillaceous rocks may be considered to belong to the class of materials that lie between rocks and soils and, therefore, share a number of characteristics with them. The material is considered as a composite, made of a soil matrix interlocked by bonds. In that simplified perspective, matrix can be seen as associated to the characteristics of the original pedologic formation and would therefore carry a response typical of a soil. Bonding is a general concept that represents any feature resulting from the posterior evolution of the soil towards a structured material or a rock. It can be associated for example to cement deposition (e.g. carbonate). In accordance with this concept, bonds are endowed with behaviour typical of quasi-brittle materials like concrete or rock. Specifically, a damage law is used to express the stress-strain relationship in the bonding and a damage parameter (ratio between damaged and total area) is introduced. This damage parameter D is used to modify Kozeny-Karman law to express the increase of the permeability with damage:

$$k = k_0 \left(\frac{1-\tilde{n}_0}{1-\tilde{n}}\right)^2 \left(\frac{\tilde{n}}{\tilde{n}_0}\right)^3 \quad \text{where} \quad \tilde{n} = n + \beta\sqrt{D} \tag{4}$$

where k_0 is the intact intrinsic permeability and $\tilde{n}$ is the modified porosity that reflects bonding fissuration. β is a material parameter.

2 DESCRIPTION OF THE TEST AND FEATURES OF THE ANALYSIS

The mine-by-test involves the sinking of a shaft, with a diameter varying between 6.25 and 6.5m, by successive blasting stages approximately 1.5-3m deep. Cleaning time between blasting stages varies from 3 to 40 days. The zone considered in the simulation is located at a depth between 436 and 556m and the instrumentation was installed between 459 and 474m (Figure 1a). The initial stress state and the water pressure follow a geostatic and hydrostatic distribution, respectively, as indicated in Figure 1b. The initial stress state was taken anisotropic. Axisymmetric conditions were assumed. Blasting was modelled by simultaneous relaxation of normal stress and pore water pressure from their current value to atmospheric pressure on the new created surface. Further details on the modelling performed are presented in [5].



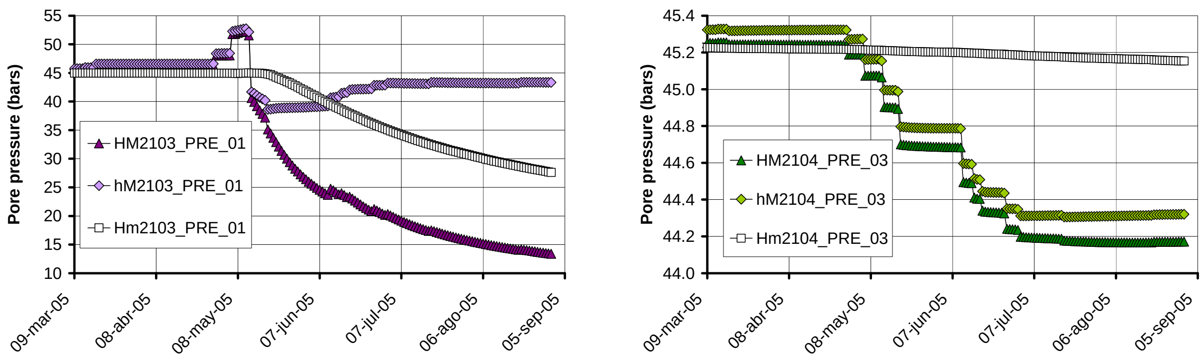
(a) (b)

Figure 1: (a) Layout of the shaft excavation test, (b) Geometry, boundary and initial conditions considered.

3 OBTAINED RESULTS

3.1 Pore water pressure

The simulated water pressure response to HM relaxation at the shaft wall is presented in Figure 2 for a sensor near the shaft wall (HM2103_PRE_01, Figure 1a) and for a sensor in the far field (HM2104_PRE_03, Figure 1b). Two additional simulations were run to illustrate the influence of the HM boundary condition at the shaft wall. In the first case, denominated hM, mechanical relaxation and null flux are applied at the shaft wall. It is clear that during shaft approach the increase of pore water pressure is exclusively induced by mechanical compression (close sensor). This compression starts early: some days after March 9th, when the excavation front is at 9m from the sensor elevation level. The short term response, during and after the passage of the shaft, is due to the mechanical expansion of the medium. For the investigated time scale, this mechanism is predominant in the far field. The second computation, called Hm, in which only pore pressure is released, shows that drainage starts at longer times. Obviously, the low permeability value of the rock is responsible for the observation of this type of behaviour.

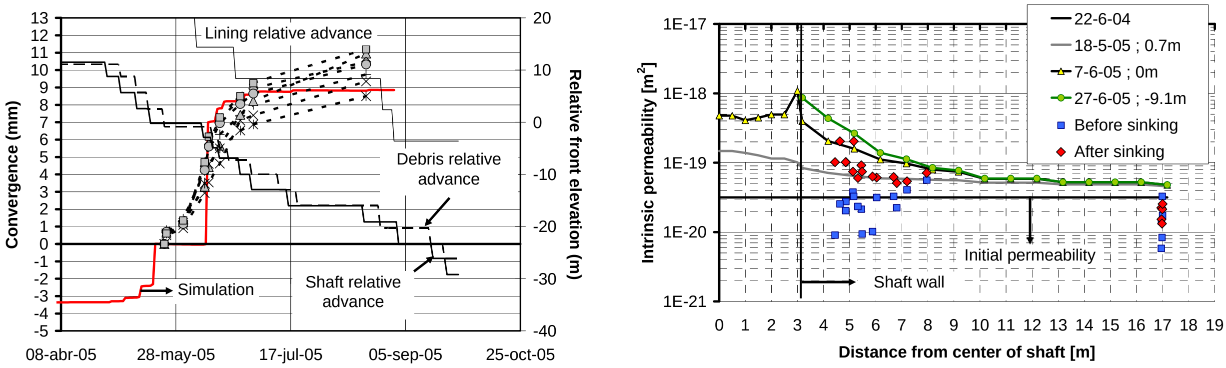


(a) (b)

Figure 2: Influence of the HM boundary condition on the pore water pressure response (a) close to the shaft (2m from the wall) and (b) in the far field (14m from the wall).

3.2 Displacements and damage estimation

In figure 3a, the convergence measurements of the shaft at a depth of 467m are compared with the simulation. If the final value of convergence is well-captured by the model, there is a discrepancy between the predicted time evolution of convergence and the measurements, probably due to a different hydro-mechanical process of equilibration and/or to the existence of significant creep after excavation. The predicted evolution before the arrival of the shaft shows a convergence of *4mm* as a result of the expansion caused by the proximity of the shaft front. In Figure 3b, the permeability measured before and after shaft sinking is compared with the prediction. The intact permeability in the model was taken in the upper measured range before sinking. During the different excavation steps, the modelled permeability comes gradually closer to the upper measurement range after sinking. The good agreement reached in term of convergence and permeability prediction increases the confidence in the model.



(a) (b)

Figure 3: (a) Comparison between the measured convergence and the simulation results, (b) Comparison between permeability measured before and after shaft sinking and the permeability estimated by the model.

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